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Direct UV-written integrated optical components

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Abstract: Direct UV writing is an emerging method for flexible, low cost fabrication of integrated optical waveguides and components. The performance of UV written components can be similar to that achieved with more elaborate fabrication techniques.

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1. Introduction

Integrated optical components are currently most often fabricated with techniques adapted from the CMOS technology platform, where circuit layouts are defined in a cleanroom using photolithography and etching. Although highly successful for the CMOS platform, the cost effectiveness of these fabrication techniques for optical circuits is questionable since the number of functions that can be integrated on a wafer here is much lower. As the market prices of optical telecom components continue to drop the interest in cheaper and more simple fabrication techniques is therefore mounting. One alternative, that addresses this problem, is to use ultraviolet (UV) laser radiation to induce waveguides directly into the core layer of a planar sample, thereby eliminating the need for photolithography and etching. Recent research has shown that waveguide fabrication with UV light is compatible with a wide range of optical materials and that it can provide basic devices with a performance that matches that achieved so far with cleanroom based fabrication techniques.

2. Materials and methods

There are two main methods currently used for UV fabrication of integrated waveguides. In the 'direct writing method' a planar sample is scanned under a focused, continuous wave UV laser [1,2]. The refractive index is increased due to the UV irradiation and the desired waveguide circuit can be defined by appropriately scanning the sample using high precision translation stages. This method is sequential in nature and therefore requires active stabilization to achieve high uniformity over extended time periods [3,4]. Alternatively, in the 'UV patterning technique' the sample is flood illuminated, typically with an excimer laser, through a metal mask that contains the desired waveguide circuit [5]. A UV patterning setup can be very simple with few moving parts and little need to maintain a high degree of stability of the UV source. The negative side of UV patterning is that it requires photolithography for the mask fabrication. In addition, the mask may be damaged by the UV irradiation, forming rough edges which are transferred into the waveguide sidewalls, thereby increasing the propagation loss [6].

Current implementations of UV writing are mostly carried out in silica-based, germanium doped glasses and utilize the same phenomenon of photosensitivity as used for fiber Bragg grating fabrication. When combined with high pressure hydrogen or deuterium loading [7] the attainable index change in germanosilica can be up to 10^{-2} which is in the same range as that used with cleanroom based waveguide fabrication techniques. The glass samples may be deposited using a variety of techniques, including plasma enhanced chemical vapor deposition or flame hydrolysis. UV induced index changes in germanosilica occur through a series of poorly understood reactions, however, it is well known that the induced changes can relax back to the original state with an broad distribution of activation energies centered at ~2 eV [8]. Hence, thermal annealing or operation at elevated temperatures for prolonged periods can lead to a reduction of the induced index change. To minimize such instability it is therefore common to subject the UV written sample to a post-fabrication anneal at up to several hundred °C. This removes the unstable part of the index change, leaving a structure that will exhibit a much more stable long-term performance [8]. UV written optical devices treated in this way have been shown to remain stable during thousands of thermal cycles up to 80 °C [9].

Direct UV writing is compatible with a wide range of sample types, including bulk glasses with exotic material properties that are not available with cleanroom based deposition techniques. Examples hereof include lead silicate glass [10], ion exchangeable bulk oxide glass [11] and chalcogenide (gallium lanthanum sulphide) glass [12,13]. Active waveguides have also been demonstrated in erbium doped silica [14], direct bonded intersubstrate ion-exchanged neodymium-doped germano-borosilicate glass [15] and Nd-doped fluoroaluminate glass [16]. Finally, waveguides may be UV written in polymer [17], which is a low cost material with significant non-linear properties.

3. Performance

In early work, the silica-based samples used for UV writing had a core layer with a refractive index larger than that of the surrounding buffer and cladding layers. Although low propagation and bending losses could be achieved, the coupling loss to standard optical fiber was 1-3 dB due to the elongated mode profile resulting from the index contrast of the core layer [18]. By co-doping the core layer with boron and germanium in the correct relative proportions it is possible to achieve a refractive index that matches that of the buffer and cladding layers [19]. Waveguides written in such index matched samples will exhibit nearly circular mode profiles and may thus be optimized for coupling to standard SMF-28 fiber [20]. Another very promising feature of index matched glass is that it allows fabrication of waveguides with a continually controllable, even zero, birefringence [21]. By optimizing the UV writing parameters propagation losses below 0.03 dB/cm at 1.55 μm have been demonstrated [20]. The index step may be as large as ~0.02, thus permitting fabrication of more compact components [22].

It is also possible to integrate UV written waveguides with other types of waveguides on the same chip. An example of this is silicon rich nitride (SRN) waveguides, which feature a very high index contrast and therefore can be used for ultra-compact lightwave circuits with small cores and bending radii down to ~10 μm. One consequence of this compactness is a very high coupling loss to standard fiber. To alleviate this problem waveguides have been UV written alongside SRN waveguides, serving as access waveguides and thereby lowering the coupling loss to standard fiber [23]. This technique should be generally applicable for hybrid chip designs where there is a need for low loss, low birefringence waveguides for fiber access and/or signal conditioning.

UV-patterned waveguides in silica with non-linear properties have been demonstrated through a combination of thermal and electrical poling. After careful optimization of the glass structure an electro-optic coefficient of 0.093 pm/V with minimal polarization sensitivity could be achieved [24]. With only a little more progress in this field it should become possible to fabricate silica-based Mach-Zehnder electro-optic switches. In addition, waveguide lasers have been UV written in neodymium-doped glass [15]. This work is an example of the freedom in choice of glass source and structure which is available when making waveguides with direct writing. The samples used here were based on bulk glass materials that are simple to produce and can readily be tailored to incorporate large amounts of exotic components that are usually not available with wafer deposition techniques.

A special feature of direct writing is that waveguide parameters such as core width and index step can be varied during the scanning process by controlling the UV spotsize, the incident power and the scan speed. This is useful for a variety of applications, such as minimizing bend loss, optimizing fiber-to-waveguide coupling, introduction of phase delays and fabrication of gratings. An example of the extended index-engineering capabilities of direct writing was presented recently, where two focused beams intersect at an angle to form a small spot containing an interference pattern [25]. Writing with such a spot does not yield a waveguide with a grating, however by modulating the UV light at a frequency matching the scan speed and grating periodicity a Bragg grating may be incorporated in the waveguide structure. Computer controlled de-tuning of the modulation frequency facilitates precise control of the Bragg wavelength over an extremely wide range.

Basic integrated optical building blocks such as directional couplers and 1×2 splitters have been fabricated with UV light [19,26-28], exhibiting excess losses as low as 0.05 dB. Devices with multimode interference regions, such as a multimode interference coupler may also be UV written [29]. Recently, several more advanced applications of UV writing such as an optical add-drop multiplexer [30] and a variable optical attenuator (VOA) [31] have been reported. The performance of these devices were similar to the best results obtained in silica with more elaborate, photolithographic and etching based technologies. To investigate the potential of UV writing as a stable platform for industrial scale production a series of VOA test production runs, totaling more than one thousand components, were recently conducted over a period of nine months [31]. During this period the UV setup was not manually maintained in any way. The batch-to-batch performance variations were similar to the (small) variations seen within a single batch; hence UV writing provides a stable platform for production of this type of component over extended periods of time. From this work the production capacity of one UV laser was estimated to be tens of thousands of multi-channel VOA chips pr. year.

4. Conclusion

Fabrication of high performance integrated optical components with UV radiation is a simple and low cost alternative to more elaborate, cleanroom based fabrication techniques that rely on photolithography and etching.

Results obtained so far show that the technique offers a large degree of flexibility in terms of glass material systems, patterning capability and functionality. UV writing can be used as a simple method for integrating low index, low birefringence waveguides with other types of waveguides on the same chip. Although UV writing remains an experimental technology, it has already shown promise as a stable platform for large scale production over a period of many months without maintenance.

7. References

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